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REVIEW

Rapid prototyping techniques for anatomical modelling in medicine

M McGurk MD FRCS FDSRCS DLO[1]
Professor of Oral and Maxillofacial Surgery

A A Amis PhD FIMechE[2]
Reader in Orthopaedic Biomechanics

P Potamianos PhD[2]
Research Fellow in Orthopaedic Biomechanics

N M Goodger MB ChB[1]
Lecturer in Oral and Maxillofacial Surgery

[1]Guy's Hospital, London
[2]Imperial College of Science Technology and Medicine, London

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The rapid advances in computer technology, often driven by the demands of industry, have created new possibilities in surgery which previous generations of surgeons could only have imagined. Improved imaging with computerised tomography (CT) has been followed by magnetic resonance imaging (MRI) and, more recently, it has become possible to reformat the data as three-dimensional images. Computer technology has now moved forward with the advent of rapid prototyping techniques (RPT) which allow both the production of models of the hard tissues and custom-made prostheses from computerised scanning data.

In this article we review the development and current technologies available in RPT and the applications of this advance in surgery and illustrate this with two case reports.

The explosion of scientific knowledge has led to a revolution in imaging techniques. The rather grainy images provided by the first generation of computed tomography (CT) scanners, although valued at the time, have now been vastly superseded by the high resolution of modern machines. The advent of magnetic resonance imaging (MRI) has provided even more detailed soft tissue images for the clinician, while ultrasound scanning (USS) machines have improved in resolution. The wide availability of the technology has meant that CT, MRI and USS are now a routine part of everyday hospital practice. Interestingly, these advances in diagnostic imaging have meant that less reliance is now placed on the interpretation of clinical signs and symptoms. Despite this drawback, the very real advantages offered by these imaging techniques make them indispensable to modern surgical practice and further refinements in the field of three-dimensional (3-D) imaging with all three modalities *(1–4)* have made their use even more appealing.

In the 1980s, technology became available to reform digital images of body slices by stacking them into representations of 3-D surfaces on dedicated computer work stations *(5,6)*. These stations were initially prohibitively expensive, but dramatic improvements in the power of desktop computers and their capacity to drive high-resolution monitors have made the technology readily affordable to most radiology units. Further advances have made it possible to rotate and manipulate the image on the screen (eg displaying cut sections or simulating surgery), which can improve their diagnostic quality and provide an improved conceptual framework in which to plan surgery *(7–10)*. Another approach developed at Guy's and St Thomas' hospitals has been to marry MRI and CT images *(11)* allowing the soft tissue detail of MRI to complement the fine skeletal details shown on CT. A similar co-localising process will allow positron emission tomographic (PET) data to be superimposed on CT or MRI images, which is proving particularly useful in describing the margin of tumours that are otherwise obscured by scar or oedema (Fig. 1). However, the relationship between the patient and the underlying pathology as seen on the computer screen is not always apparent; surgeons must still learn to interpret the visual information in order to envisage the 3-D geometry, such as when trying to mentally place an osteotomy cut required in a reconstructive procedure.

A new and impressive advance is the development of

Correspondence to: Professor M McGurk, Guy's Hospital, St Thomas Street, London SE1 9RT

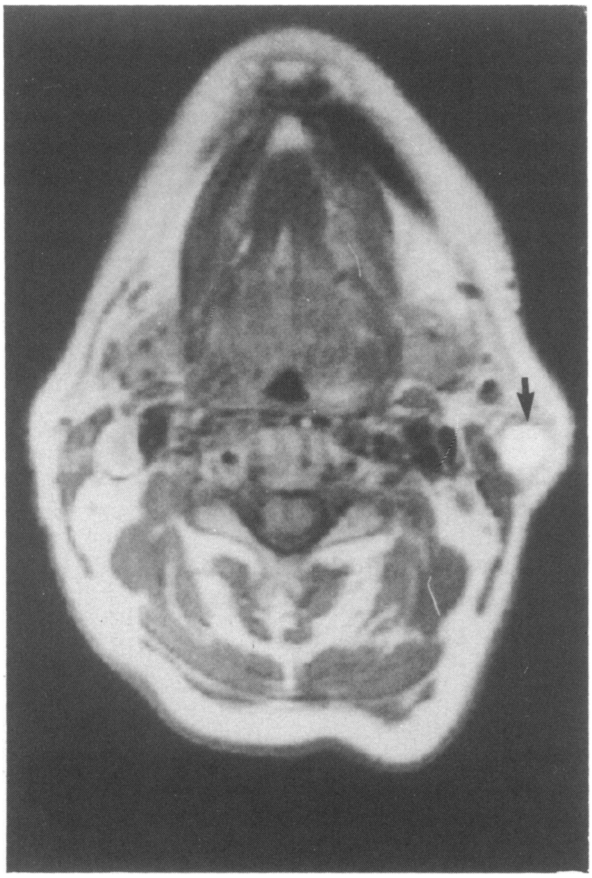


Figure 1. Combined CT and PET scan showing a tumour in the parotid gland (arrowed).

rapid prototyping techniques (RPT), a method that was originally introduced in industry to improve design and reduce product development time, now being applied to medicine. In this technique, the computer screen image is accurately reproduced in a few hours as an acrylic model which can be handled by the surgeon, allowing an immediate and intuitive understanding of the most complex 3-D geometry and can be used to accurately plan and practice an awkward operative procedure.

Development of rapid prototyping

In industry, the widespread use of computer-aided design (CAD) produced both the momentum and desire to translate 3-D images into physical models. Initially, this was achieved by computer numerically controlled (CNC) milling machines that used the 3-D data to cut the shape of each CT 'slice' from a solid block of styrofoam or polyurethane. This late 1980s technology was used to produce models of heads and faces, but these were initially rather crude, with 'stepped' surfaces reflecting the 'sliced' CT data. This system has evolved and accurate models *(12,13)* and simple prostheses *(14–21)* can now be produced. The limitation to this method is that the level of complexity demanded by designers in industry and that required for detailed anatomical models cannot be reproduced even by five-axis milling machines *(22)*, and this has led to the development of RPT. This process, in contrast, works on the principle of building up the model in layers or slices by material deposition rather than cutting down a block of polyurethane. As an anatomical part can be scanned into a computer system slice by slice, similarly an object can be faithfully reproduced slice by slice using the 3-D computer data in conjunction with a RP machine. As the model is created tomographically, it contains all the details of its internal contour geometry, not just the outer surface as in the milling technique. Furthermore, modern software allows for interpolation between the coarse cuts of a CT scan, leading to models with smooth 3-D curved surfaces which the RP machine can create by building the model in much finer slices. There are currently a number of RP technologies on the market, based on special sintering, layering or deposition methods as described below *(23)*.

Stereolithography (SLA)

This is the leading technology, with over 500 SLA machines installed worldwide, developed by 3-D Systems Inc, of Valencia, CA. Stereolithography creates 3-D models out of acrylate photopolymer or epoxy resin, by tracing a low-powered ultraviolet laser across a vat filled with resin. The material is cured by the laser to create a solid thin slice. The solid layer is then lowered just below the surface and the next slice formed on top of it, until the object is completed *(23–25)*.

A recent development by Zeneca is a translucent resin which changes to red when acted upon by a higher laser energy. This can be used to display local regions of interest, and an obvious application would be for the surgeon to draw round a tumour on the medical image slices and have it built into the model (Fig. 2).

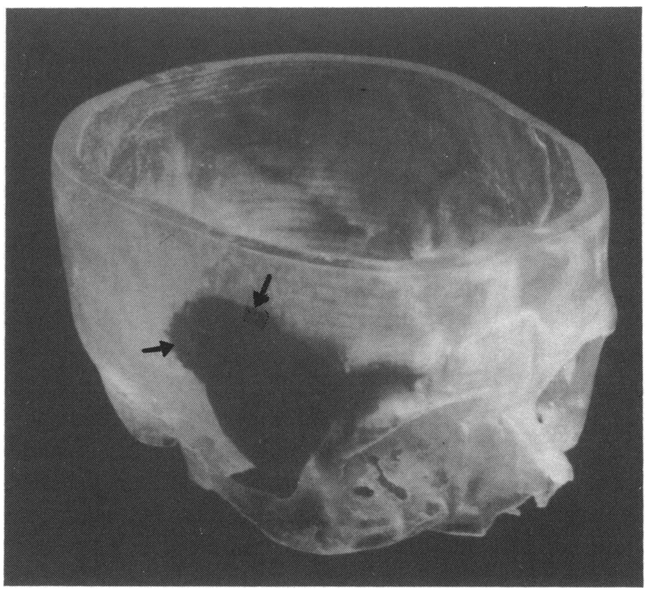


Figure 2. A stereolithographic model showing an area of interest highlighted in coloured resin (arrowed).

Selective laser sintering (SLS)

This technology was commercialised by DTM Co, of Austin, TX. SLS creates 3-D models out of a heat-fusible powder, such as polycarbonate or glass-filled composite nylon, by tracing a modulated laser beam across a bin covered with the powder. Heating the particles causes them to fuse or sinter together to create a solid thin slice. The solid layer is then covered by more powder and the next slice formed on top of it, until the object is completed.

The same process can be performed with a combination of low-carbon steel and thermoplastic binder powder, resulting in a 'green state' part. The binder is then burned off in a furnace and the steel particles are allowed to sinter together. The resulting steel skeleton is subsequently infiltrated with copper, resulting in a metal-composite part. A similar technology is also used by EOS GmbH, of Planegg, Germany, which can fabricate metal parts out of bronze alloy powder that can be sintered into a solid mass.

Solider process

This technology was developed by the Israeli firm Cubital. The Solider Process creates 3-D models out of light-curable photopolymers. The process is similar to techniques employed in the manufacturing of printed circuit boards; instead of using a laser beam, an ultraviolet lamp hardens the build material by shining on it through a photomask, creating a solid thin slice. The solid layer is then covered by more polymer and the next slice formed on top of it with a new mask, until the object is completed, enclosed in a wax composite which is then melted away.

Fused deposition modelling (FDM)

This technology was developed by Stratasys Inc, of Eden Prairie, MN. FDM creates 3-D models out of heated thermoplastic material, extruded through a nozzle positioned over a computer-controlled *x–y* table. The table is moved to accept the material until a single thin slice is formed. The next slice is built on top of it until the object is completed. FDM utilises a variety of build materials, such as polycarbonate, polypropylene and various polyesters which are more robust than the SLA models. A similar approach is used by Sanders Prototype Inc, of Wilton, NH, to produce 3-D models by extruding thermoplastic material through ink-jet printer nozzles. FDM models can also be made in wax, enabling custom-made implants to be investment cast for individual patients.

Laminated object manufacturing (LOM)

This method was developed by Helisys Inc, of Torrance, CA. LOM creates 3-D models by laminating adhesive-coated sheets of paper; the adhesive is heat-activated by a focused laser beam, which cuts around the edges of each layer on an *x–y* table. Further sheets are bonded on top until the model is built. Although these models are robust, it is difficult to remove unwanted regions of paper from areas of complex geometry.

3-D printing

This technology was developed at MIT and is being commercialised by a number of companies. 3-D printing creates models by spraying liquid through ink-jet printer nozzles on to a layer of metallic or ceramic precursor powder, thus creating a solid thin slice. The printing process is repeated for each subsequent slice until the object is completed as a 'green-state' part. The part is then fired in a furnace to sinter the powder. The resulting skeleton object is subsequently infiltrated with metal, resulting in a full-density part.

Multiphase jet solidification (MJS)

This technology was developed by the network of Fraunhofer Institutes in Germany. MJS creates 3-D metal or ceramic models out of various low-viscosity materials in powder or pellet form, by extruding the build material through a jet in liquid form. Each layer that is deposited solidifies on to the previous one, until the entire object is created. This technology is still in the development phase.

Clinical applications

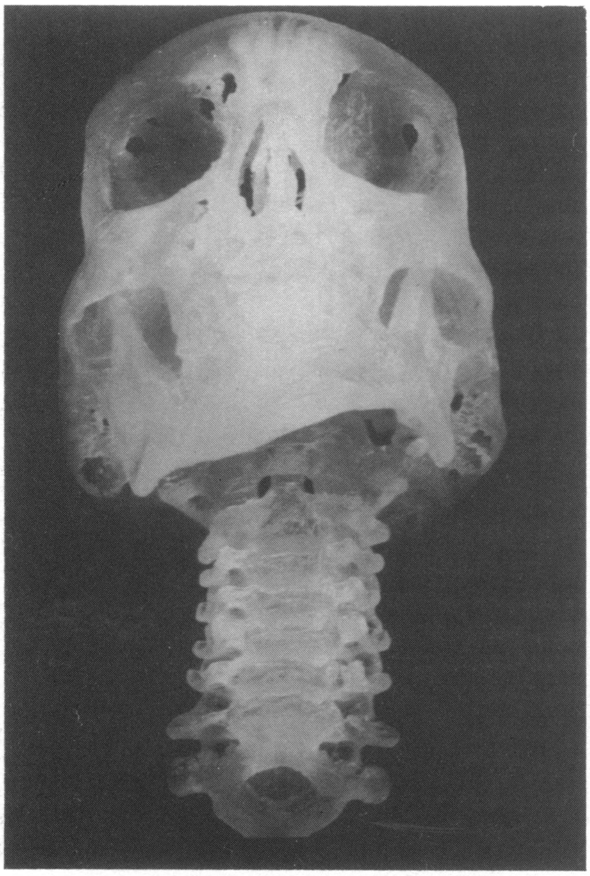
The advantage of RPT is complete visual appreciation of bony anatomy hitherto unavailable. The modelling process is very accurate *(22,26,27)*, reproducing CT data to a tolerance of 0.1 mm. The major source of error is the CT scanning process itself, where inaccuracies of up to 1 mm can occur. Thus, medical imaging is the limiting factor when producing RP bone models *(26)*. The obvious application of this technology is in bone surgery, for example, where the orthopaedic surgeon can be challenged by complex congenital deformity, traumatic reconstructive procedures or joint revision surgery. RPT models allow surgery to be accurately planned, osteotomy cuts can be practised on the model, plates may be preformed and prostheses such as implants custom made to each individual patient. The advantage of planning and practising the procedure *in vitro* should be reduced operating time and improved results. Similar geometric problems are encountered in craniomaxillofacial surgery, but the tolerance to which the surgeon works is much smaller, for in re-establishing the dental occlusion fractions of a millimetre are important. The opportunity of holding and visualising the facial bones as well as practising the operative procedure is a major advantage *(28)* as illustrated in two case reports below.

This technology starts to move surgery more to a science than an art form. However, the major disadvantage with RPT at present is that the models are expensive (approximately £2000 for a model of the facial skeleton) and, as yet, RPT has not been widely utilised in the UK, although more enthusiasm has been shown for its application in Europe.

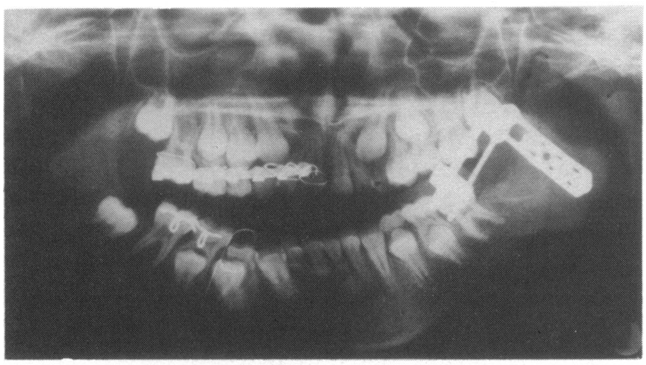
Case reports

Case 1

A girl with mild hemifacial microsomia was referred, aged 9 years, with progressive facial deformity. Reduced growth potential in the left mandible had resulted in the deviation of the lower jaw to the affected side and lack of vertical growth caused a sympathetic retardation in development of the left maxillary arch resulting in an occlusal cant. The intention of treatment was to lengthen the mandible using a distraction osteogenesis technique pioneered by Ilizarov *(29)*. Conventionally, the forces required to distract the two bone segments are transmitted through transcutaneous pins, but this has the disadvantage of producing facial scars. A model of the facial skeleton was generated from CT data (Fig. 3*a*), and using this an intraoral screw device was designed to attach to the ramus posteriorly through a bone plate and to the body of the mandible anteriorly through an acrylic plate cemented to the teeth. A corticotomy across the angle of the mandible between the two points of attachment was performed with a surgical bur. The screw was lengthened at a rate of 1 mm/day for a total gain of 12 mm in length (Fig. 3*b*). The design and accurate placement of the device within the limited space available would not have been possible without a preformed model. Further, by cutting the model at the planning stage, the team gained immediate insight into the relative movements of the mandibular fragments needed to optimise the occlusion; this had not been apparent from the images available, and was a major factor in the design of the procedure.



(a)



(b)

Figure 3. Case 1 showing *(a)* the SLA model illustrating the underdeveloped mandible and *(b)* a DPT radiograph showing the mandible after distraction.

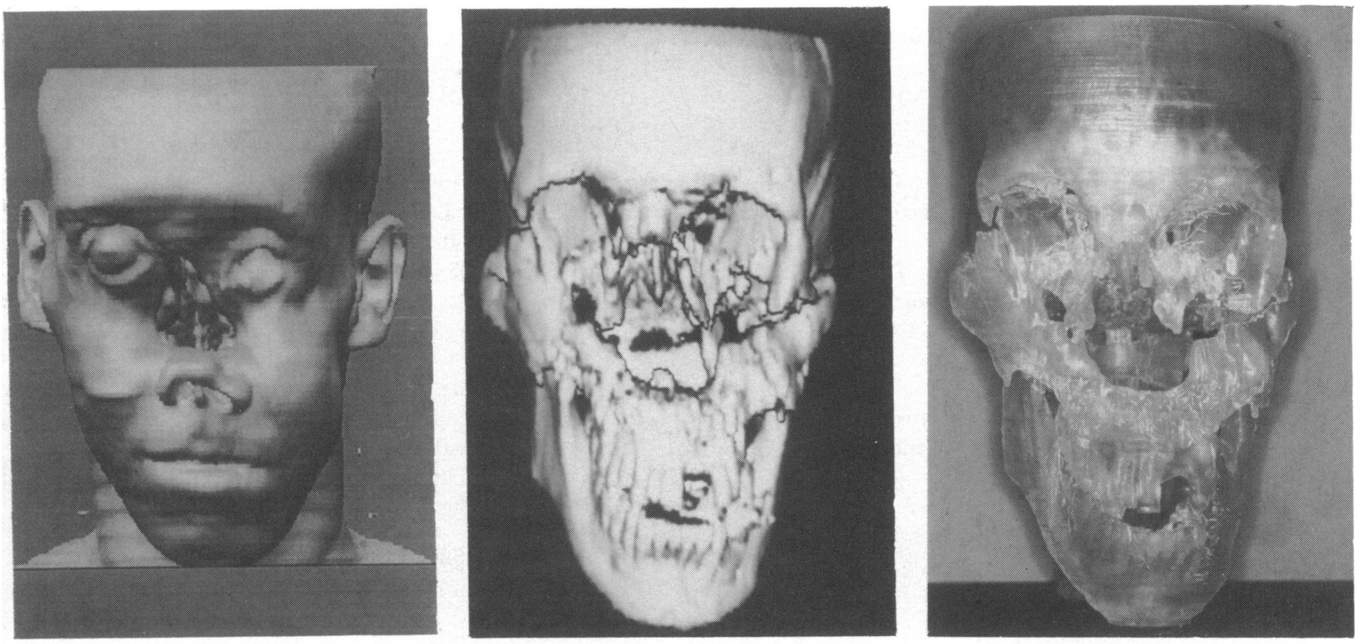
Case 2

A patient was referred for secondary reconstruction following a road traffic accident during which he suffered complete disruption of the maxillary skeleton, a fracture of the left ramus of the mandible, loss of the left eye and nose. Initially, the mid-face had been packed to stem the haemorrhage, but this ultimately led to a permanent inferior displacement of the maxilla. 3-D computer images of the facial hard and soft tissues were generated as well as two computer models (Fig. 4*a–c*). The first stage in the reconstructive procedure was to restore the normal facial proportion by re-establishing the maxilla and mandible in their correct position. The operative procedure was complicated by the presence of scar tissue which restricted the mobilisation of the bone units. The models proved of value in allowing full appreciation of the anatomical deformity, the planning of osteotomy cuts and subsequently ensuring the correct alignment of bone fragments with customised bone plates.

Unfortunately, the reader can only see a 2-D representation of the RP model used, which means that the impact of its availability and immediate understanding of the 3-D geometry is lost.

Conclusion

The arrival of RPT in surgery is a reminder of how progress in modern medicine is essentially technology driven. In the UK, RPT has been used to help plan treatment in more than 20 patients; however, the cost of the modelling process is currently a significant limitation to its use. The future of this technology is likely to be dependent on cost, which should fall as the difficulties in processing medical image data are overcome, as the computer software develops and as the RP model makers gain experience. Because this is new technology, rapid advances are likely to lead to new fabrication methods.



(a) (b) (c)

Figure 4. Case 2 showing *(a)* 3-D MRI of the facial soft tissues *(b)* 3-D CT scan showing the bony facial skeleton and *(c)* the SLA model.

The expense of the RP model can, of course, be offset against savings in operating time and if RP models allow better planning of procedures such as revision of a loosened joint replacement accompanied by gross bone loss, then the expense may also be justified in terms of a reduction in further failures. These possibilities will require audited trials to prove cost-effectiveness and improved treatment outcomes. It will be of interest to see where this technology eventually leads, what advantages it may bring to the patient and how it will further aid the surgeon as it evolves.

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